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Journal:	*International Journal of Science Education*
Manuscript ID:	TSED-2007-0423.R1
Manuscript Type:	Research Paper
Keywords:	physics education, nature of science, laboratory work, university
Keywords (user):	nature of scientific measurement

The relationship between students' views of the nature of science and their views of the nature of scientific measurement

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Abstract

The present study explores the relationship between students' views on the nature of science (NOS) and their views of the nature of scientific measurement. A questionnaire with two-tier diagnostic multiple choice items on both the NOS and measurement was administered to 179 first year physics students with diverse school experiences. Students' views on the NOS were classified into four 'NOS profiles' and views on measurement were classified according to either the point or set paradigms. The findings show that students with a NOS profile which is dominated by a belief that the laws of nature are to be discovered by scientists, are more likely to have a view of the nature of scientific measurement characterised by a belief in 'true' values. On the other hand, students who believe that scientific theories are inventions of scientists, constructed from observations which are then validated through further experimentation, are more likely to have a view of the nature of scientific measurement which is underpinned by the uncertain nature of scientific evidence. The implications for teaching scientific measurement at tertiary level are discussed.

Introduction

In order for a science knowledge claim to pass from the personal domain to the realm of shared scientific knowledge, the quality of the claim, i.e. the reliability and validity of the consolidated result, has to be considered and communicated (Tytler, Duggan & Gott, 2001). Understanding the relationship between experimental data and scientific evidence is fundamental to one's views of how scientific knowledge is generated. The unambiguous communication of experimental results and the comparison of measurements with other measurements, or with theory, are thus important elements which need to be explicitly developed in science laboratory teaching. The understanding of scientific measurement has also been given prominence in the descriptions of the goals of physics teaching by policy bodies such as the *American Association of Physics Teachers* (AAPT, 1998). Subsequently, the understanding of measurement has been included in the assessable outcomes of school science as reflected in international comparative studies (for instance, OECD, 2003; Lemke & Gonzales, 2006), and inventories of essential aspects of scientific literacy constructed by panels of experts (for example, Osborne, Collins, Ratcliffe, Millar & Duschl, 2003).

It has been shown in several contexts (Etkina, Murthy & Zou, 2006; Kung & Linder, 2006; Rollnick, Lotz & Dlamini, 2002) that the majority of students arrive at university with views of scientific measurement that are based on the notion that in principle a scientific measurement will yield an exact result. For many students, therefore, the ideal is to perform a single 'correct' measurement with the utmost care. In other studies (Allie, Buffler, Kaunda, Lubben & Campbell, 1998; Deardorff, 2001) it was found that students include anomalous readings in calculations of the mean without any comment. Such students are often inclined to repeat measurements only if they have reasons to query their first reading, and then with the purpose of finding a confirmatory value (Séré, Journeaux & Larcher, 1993). When presented with data that are dispersed, they often attempt to choose the 'correct' value (for example the recurring value) from amongst the values in the ensemble. When comparing two data sets, undergraduate students often make judgments on the basis of the number of repeated readings or of the frequency of identical or similar data points (Masnick & Morris, 2002).

Fairbrother and Hackling (1997) and Ryder and Leach (1999) have claimed that students' actions and reasoning while 'doing' science, are dependent on their views of the nature of science (NOS). If they believe that science reveals the 'truth', then experimental work may be viewed as a quest for generic and permanent scientific knowledge. A study by Tsai (1999) suggested that students' views of the NOS affect their actions and reasoning during experimental work. She concludes that 'if they perceive science as a collection of proven facts, they will focus on memorizing these "truths" and will attempt to prove them through codified procedures provided by the scientific method' (p. 655). Students with the NOS belief that scientific knowledge is infallible and static are mostly concerned with manipulating the instruments very carefully and proceeding through an experiment by following through the prescribed steps in order to obtain the expected result. They see the purpose of experimentation as to 'verify truths and validate the correctness of scientific laws or rediscover proven facts' (p. 668). In contrast, students with NOS views that scientific knowledge is tentative, involves human invention and depends on peer consensus, generally spend most of their time during laboratory work on conducting the experiment, discussing and analyzing the data, and sometimes linking the data to theoretical aspects of the investigation. They see the purpose of experimentation as 'illustrating the process of constructing scientific knowledge' (p. 668). The findings of Séré, Fernandez-Gonzalez, Gallegos, Gonzalez-

Garcia, De Manuel, Perales and Leach (2001) refine the broad dichotomy painted above, by concluding that science students (at university and upper secondary level) utilize different NOS views to direct their actions and reasoning in experimentation in different science disciplines. Interestingly, Hodson (1998) claims that the reverse causal relationship may also occur. If laboratory work mainly consists of recipe-type practical sessions, then these experiences may influence NOS views and develop inappropriate scientific epistemological concepts in students. Students may come to believe that science provides the 'right' answer and that generic and infallible knowledge is discovered by making use of the scientific method to conduct experiments and gather objective data.

Although considerable discussion has taken place on the role of the NOS in science education, only some consensus exists about those aspects that should be included in the school or university science curriculum. Lederman (1992) proposed that an adequate understanding of the NOS includes the notion that scientific knowledge is tentative and theory-laden; the idea that scientific knowledge depends not only on experimental data and observations but also on human inference; and the understanding that it includes social, cultural and political aspects. In addition, Lederman claims that one must be able to distinguish between inference and observation, theory and law. More recently, Tsai and Liu (2005) identified five dimensions in secondary school students' views of the NOS based on the function of empirical data, i.e. the role of social negotiation in the development of scientific knowledge; the creative contribution to this knowledge; the theory-laden approach to science; the consequences of the cultural context of the scientific enterprise; and the tentative nature of scientific knowledge. Several of these dimensions overlap with Lederman's aspects of the NOS, and for the purposes of this study the Lederman definition has been adopted.

Studies probing students' NOS conceptions have shown that they often only have a partial understanding of the NOS (see for example, Abd-El-Khalick, Lederman, Bell & Schwartz, 2002), and often view science as an objective endeavour (Moss, Abrams & Robb, 2001). When probing secondary and tertiary students' conceptions on the relationship between theory and evidence, a study by Ryder, Leach and Driver (1999) on undergraduate students' views on the relationship between scientific claims and data, revealed that the majority of the students firmly believe that the reliability and validity of scientific knowledge depend solely on empirical data. They lay much emphasis on the quality and quantity of experimental data which according to most students is equivalent to scientific evidence (Dagher, Brickhouse, Shipman & Letts, 2004). Repetition of an experiment thus results in the collection of more data such that they are reproducible, more accurate and hence reduce doubt concerning the reliability of the final result.

Most of the studies on students' views on the various aspects of the NOS assume that their views on these aspects of the NOS are independent of each other. In this respect, Hogan (2000) differentiates between proximal and distal images of the nature of science. Proximal views of the nature of science are concerned with ways in which students use their own experiences in the construction of school science knowledge. In contrast, students' distal images of the nature of science include their views about the strategies and procedures used by scientists and about the outcomes of science as an enterprise. Vhurumuku, Holtman, Mikalsen and Kolsto (2006) have shown that students' understanding of proximal images of the nature science is related to their ideas about the practice of professional scientists, but that laboratory experiences may affect their distal images of the nature of science.

The present study uses a new method (Ibrahim, Buffler & Lubben, in press) to describe physics students' views of the NOS holistically. The focus is on distal views of the NOS due to the fact that most of the students in the sample have little or no experience of hands-on laboratory work, one of the main influences on proximal views of the NOS (Hogan, 2000). Compact NOS 'profiles' (see below) have been constructed, which may be understood as sets of key descriptors which represent the variation in the views of individual students within the entire sample in a succinct way. Based on these NOS profiles, the relationship between students' views of the nature of science and their views of the nature of scientific measurement is then explored.

Methods

Design of the questionnaire

The VASM (Views About Scientific Measurement) questionnaire was designed for the study (VASM, 2005). The written instrument is made up of eight questions (probes) dealing with scientific measurement and six probes exploring certain aspects of the NOS. The probes on measurement focus on comparing 'everyday' measurements with scientific measurements; the meaning of the term 'exact'; the reasoning behind measurement decisions made when collecting, processing and comparing data; and the nature of measurement uncertainty. Several of the probes were adapted from instruments used in earlier studies on measurement (Buffler, Allie, Lubben & Campbell, 2001). The probes on the NOS deal with different issues around the nature and origin of scientific knowledge; the relationship between scientific experiment and theory; the role of scientific experiments in the production of knowledge; and scientists' use of the scientific method and their own creativity. One probe dealing with the nature of scientific knowledge was derived from Moss et al. (2001) and the probe investigating the use of creativity and the scientific method during an experiment was adapted from the VNOS-Form A by Lederman and O'Malley (1990). The remaining NOS probes were newly designed for the study. Social and cultural aspects of the NOS were not included in the VASM.

Structure of the VASM probes

Lederman (1999) has questioned the validity of the common practice of collecting data on views of the nature of science through questionnaires with Likert-type items. The present study uses open-ended written items, a decision which took account of suggestions (Hogan, 2000) that surveys of distal images of the nature of science require general questions about professional scientists, as opposed to specific scenarios which are more suitable when investigating proximal images of the nature of science. All the probes in the VASM questionnaire have a common style and are based on the same context which involves scientists making measurements of the magnetic field of the Earth and comparing these measurements with theories about the composition of the Earth. Each probe presents a scenario followed by a number of different options, which are presented in the form of conversations. Figure 1 illustrates one of the measurement probes in the VASM questionnaire, which deals with the comparison of two sets of measurements. In this two-tier multiple choice format, the respondent is asked to select only one of the alternatives provided, and provide a detailed written justification for the choice. In other probes, the option 'I have a different idea' or 'I have another view which I will explain' is provided allowing respondents to have the opportunity to formulate alternative views on the issue discussed in the probe.

[Figure 1 about here]

The probes in the VASM questionnaire were designed and sequenced to allow for a natural flow in the explanations given. Previous studies using similar types of probes (Allie et al., 1998) showed that the use of real life figures and names can either encourage or discourage the selection of an option. Consequently, in order to improve construct validity of the responses, neutral cartoon figures were used and labelled by letters to present the various options for each question. The language used in the items was chosen to be as straightforward as possible and the words were reduced to a minimum. Content validity of the probes was improved by using peer reviews by university professors (three each from both science and non-science disciplines) and five post graduate physics students. The VASM probes were also piloted with different groups of undergraduate and postgraduate students and some items were adjusted where necessary for clarity of expression and focus.

The VASM questionnaire was completed by 179 physics students on entry into their first year of the BSc undergraduate program before any instruction. These students came from a diverse schooling background, ranging from those students who would have been at schools where they would have had significant exposure to laboratory work, to those who would have had poor science teaching and no practical experimentation. Respondents were asked to complete the set of written probes individually, in strict sequence and under examination conditions. The average time for the students to complete the set of probes was about an hour.

Analysis

Coding schemes were designed for each probe using grounded theory methods (Strauss & Corbin, 1998) especially interpretational analysis (Gall, Gall & Borg, 2007). In order to improve criterion validity of the analysis, this process was undertaken independently by two researchers after which the codes were compared and discussed, and agreement was reached on the arrangement and grouping of codes for their mutual exclusivity and logical hierarchy. Based on the underlying reason given to support the selected action, each category of response was divided in sub-categories allowing for subtle variations to a broad theme. Where appropriate, the same codes were used across different probes. Identically coded responses were compared for consistency, and similarly coded responses for mutual exclusiveness. For each probe, the frequency of different responses was scrutinized and particular categories grouped together to form between 5 and 6 main classes of ideas.

Results

Views on the nature of science

A detailed analysis of the NOS views of the students as revealed in each individual probe has been reported elsewhere (Ibrahim et al., in press). Using the students' responses to each of the six NOS probes, 'profiles' of the students' views were constructed in the following way. Frequently occurring combinations of particular views were identified across all 179 sets of probes. A student was only allocated to a particular NOS profile if all six responses were consistent with the descriptors for that profile. It was found that four profiles were sufficient to capture the NOS views of 86% of the students, which are presented in Table 1, and have been labelled 'modellers', 'experimenters', 'examiners', and 'discoverers', respectively. These profiles are not hierarchical but our view is that the modellers hold the most appropriate view of the NOS as defined by Lederman (1992).

[Table 1 about here]

All four profiles contain the idea that scientific knowledge explains or describes the behaviour of nature and that scientific theories are generated, tested, validated or revised in the light of experimental results. The four profiles differ mainly with respect to views on the origin of scientific knowledge, the correctness of experimental methods, and the relative importance that experimentation plays in relationship to theory.

Profile 1 (the modellers) is characterised by the notion that hypotheses and scientific theories are constructed by scientists and experimental evidence is required in order to validate these theories. Furthermore, theories provide explanations about the complex behaviour of nature. Scientists use their creativity in constructing hypotheses or theories, and during experimentation. In cases where there are discrepancies between theoretical and experimental results, both need to be scrutinized.

Profile 2 (the experimenters) differs from Profile 1 in two aspects. The experimenters believe that scientists should still use experimental evidence to test hypotheses, but should strictly use the scientific method, and not their creativity, when doing experiments. The results from these rigorous experiments carry a higher precedence over theories.

Profile 3 (the examiners) differs from Profile 2 in three aspects. The examiners hold the view that the laws of nature are fixed and stable. These laws are out there to be discovered (and not constructed) by scientists. Experimental work is essential but not informed by hypotheses or theories. Scientists may use both the scientific method and their imagination. Experimental data unearth the laws of nature, and the results from experiments carry a higher precedence over theories.

Profile 4 (the discoverers) differs from Profile 3 in two aspects. Although the discovers also believe that the laws of nature are out there to be discovered (and not constructed) by scientists, only experiments using the scientific method can be used to generate these laws (or theories). If experimental data conflict with a previously established theory, then both the theory and the experimental data need to be checked.

The four profiles are illustrated in Tables 2, 3, 4 and 5 respectively, where in each case the full set of responses of a single student are presented.

[Table 2 about here]

[Table 3 about here]

[Table 4 about here]

[Table 5 about here]

Views on the nature of scientific measurement

The model of students' understanding of the nature of scientific measurement termed the 'point paradigm' and 'set paradigm' of scientific measurement (Buffler et al., 2001) was used to interpret the responses dealing with scientific measurement (see Table 6).

[Table 6 about here]

In brief, the key difference between the two paradigms is that students using the point paradigm draw conclusions about the measurand directly from individual data points, while those using the set paradigm draw conclusions about the quantity being measured (the measurand) from the properties of the distribution constructed from the whole ensemble of available data.

Each category of response to each probe was associated with either the point or set paradigm. For each student, the whole set of measurement probes were considered together and the participant's overall view of measurement was classified according to either the point or set paradigm. A participant's overall view was associated with the point paradigm if there were a total of five or more responses associated with the point paradigm. The same criterion was applied for overall classification according to the set paradigm. A respondent's overall view was not classified when two or more responses were not able to be coded. The following two summaries of two students' responses illustrate the two paradigms.

Student A was classified as using reasoning associated with the point paradigm since he wrote concerning the 'exactness' of scientific measurement, 'Sometimes an experiment should be repeated and the results should be compared. The result would be the one which keeps on appearing', and 'Scientific measurements need to be exact in order to obtain the results you need to know'. This was supported by responses to probes asking for a digital and analogue scales to be read, with explanation. When asked whether an observation of the same phenomenon should be repeated, the student wrote, '(Yes.) This will confirm their discoveries and therefore they'll know that they are right'. The next probe in the sequence then provided a list of five repeated observations of the Earth's magnetic field from which the student chose the value which appeared twice as the final result, saying, 'It appeared twice which means that that was confirmed the second time'. Furthermore, when provided with two sets of data, together with their averages (see Figure 1), the student decided that the two results are in agreement since, '… the averages only vary in a few decimals. In mathematical terms this will not be considered'.

In contrast, Student B was classified according to the set paradigm, since she wrote, 'No number of measurements can give an exact result, as measurement is inherently flawed, and is always inaccurate at some scale'. Furthermore, 'Exact means that the measurement of a quantity recorded corresponds precisely to the physical value of that quantity. The measurement (process) can also affect the value being measured, which prevents it from being exact'. When asked to read a digital and analogue scale, the student wrote, 'If the scientists' instrument was correct to within 0.001 mT, then they now have an approximation to within 0.001 mT of the exact value. However, they cannot be any more accurate than this', and 'The temperature is approximately 24 °C measured to the nearest degree, if the thermometer is accurate. There are no markings between 23 °C and 24 °C or between 24 °C and 25 °C, so it is impossible to read any more accurately than this, so as whether it is closer to 23.9 °C or 24.0 °C or 24.1 °C, for example'. When asked about the need for repetition of observations, 'The scientists should also repeat it … a few times to lessen the chance of anomalies or experimental errors'. When provided with a set of data and asked about the most appropriate result to quote, 'The average of the 5 measurements is 0.133 mT, but this would imply an unrealistic accuracy'. Finally, when comparing two sets of data (Figure 1), 'The results might be in agreement. The averages agree to 2 decimal places, and not even all the measurements within a group agree to 2 decimal places, so if all the measurements in a group can be considered to be consistent, then the two groups can be considered to agree to the required accuracy'.

Relationship between views of the nature of scientific measurement and views on the NOS

Each student's views on measurement as described by the point or set paradigm was related to their NOS profile. The results obtained are shown in Table 7.

[Table 7 about here]

The vast majority of students in the sample (73%) provided responses associated with the point paradigm, whereas the reasoning of only one in five students (20%) entering the undergraduate science programme could be associated with the set paradigm. The data in Table 7 also reveal that the largest group of students in the sample were modellers since 44% (78 in 179) have NOS views which are described by Profile 1. On the other hand 16% (29 in 179) were classified as experimenters (Profile 2) and 19% (34 in 179) as examiners (Profile 3). The discoverers (Profile 4) represent only 7% (13 in 179) of the total sample.

[Table 8 about here]

Table 8 shows the ratios of the students associated with the point paradigm over those associated with the set paradigm for each of the four profiles. It was found that a higher proportion of students described by Profile 3 were associated with point reasoning (ratio of 10.0), and a higher proportion of students described by Profile 1 were associated with set reasoning (ratio of 2.7). In order to explore this idea further, the dominant idea which differentiates between these two profiles was considered on its own and correlated against students' ideas about scientific measurement as described by the point and set paradigms. The second probe in the VASM questionnaire asked students about their views on the origin of scientific laws and theories. Most students either suggested that nature has its own laws which are discovered by scientists through observation, or that scientific theories are constructed by scientists from observations for better understanding of the complex behaviour of nature (see Table 1).

[Table 9 about here]

Table 9 explores the relationship between these NOS views and views on the nature of scientific measurement. From the 131 students associated with the point paradigm, 49% (64 in 131) were of the opinion that nature has its own fixed laws which are discovered through experimentation, while 43% (57 in 131) believed that scientists construct theories based on observations. Around 74% (26 in 35) of students classified according to the set paradigm focused on the notion that theories are inventions of the scientist, and only 20% (7 in 35) of the students with set reasoning believed that the laws of nature already exist.

Discussion and conclusion

The NOS views of 86% of the students were captured within four NOS profiles. Furthermore, 73% of the students in the sample had views of the nature of scientific measurement which were associated with the point paradigm, while the views of a further 20% students were associated with the set paradigm. The fact that high proportions of the views of students in the sample could be modelled in both cases allowed the relationship between the two aspects to be explored. All four NOS profiles contain the descriptor that scientific theories are tested, validated and confirmed through experimentation. The results suggest that students categorised according to the modellers profile will have views of scientific measurement described by the set paradigm. On the other hand we found a greater likelihood for students categorised according to the examiners profile to have views of scientific measurement described by the point paradigm. This finding is softened by the fact that the views of only 20% of the entire sample were described by the set paradigm, a finding which is consistent with other published research for students at the start of their university studies (see for example Deardorff, 2001; Séré et al., 1993; Rollnick et al., 2002).

The distinguishing feature between the modellers and examiners profiles is the view of the nature and origin of scientific theories and laws. Students with a view of the nature of science which is dominated by a belief that nature follows its own patterns and that the laws of nature are to be discovered by scientists, are more likely to have a view of the nature of scientific measurement characterised by a belief in 'true' values. These students are more likely to view the purpose of scientific measurement to uncover the truth about nature. Measurement error occurs when mistakes are made and hence the idea arises that the uncertainty in a measurement result can in principle be reduced to zero. On the other hand, students with a view of the nature of science dominated by a belief that scientific theories are inventions of scientists, constructed from observations which are then validated through further experimentation, are more likely to have a view of the nature of scientific measurement which is characterised by the uncertain nature of scientific evidence. Since measurement uncertainty can never be reduced to zero, observational data (numbers) need to be transformed using a statistical model into a form which is compatible with theory.

The relationship between experiment and theory is crucial for understanding how to distinguish between scientific and non-scientific knowledge (Leach, 1999), since the acceptance or rejection of a theory is based solely on experimental evidence. The acquisition and construction of scientific knowledge, and hence its reliability and validity, was seen by most students to be dependent on experiments and experimental results. This is consistent with the outcomes of separate studies into university students' views of the interplay between scientific theories and experiments (Ryder et al., 1999; Ryder & Leach, 1999; Séré et al., 2001). For example, Séré et al. (2001) presented students with measurements in different science disciplines (biology and physics) and in everyday situations. They found that students used different epistemologies and ontologies of the nature of science for processing the data in the various contexts. The notion of an epistemology of the *nature of measurement*, as distinct from an epistemology of the nature of science, is introduced. Therefore the relationship between scientific knowledge and scientific experimentation (which relies on scientific measurement) appears to underpin the view that a student will have concerning the nature of science as an enterprise.

According to Ryder and Leach (1999), an understanding of scientific measurement includes the ability to relate a scientific claim (theory) to the data (evidence) obtained from an experiment.

Hence, during laboratory work, students are expected to demonstrate an understanding of the evaluation of evidence and interpretation of experimental data (Gott & Duggan, 1996). Millar (1996) describes the understanding of evidence as the ability to evaluate the effect of uncertainty on experimental data. However, Millar, Le Marechal and Tiberghien (1999) argue that students' actions and decisions during experimental work is affected by their views on what constitute reliable experimental data and how they are related to a theory for the derivation of constructive scientific knowledge. Consequently, explicit exposure to issues around the NOS in laboratory work may help in developing the required understanding of the relationship between scientific claims and experimental data. For example, if students are presented with situations where they have to deal with experimental results with two contradicting subsequent claims (theories), then they may be encouraged to relate the concepts of uncertainty and evidence to each other, and consequently recognize the relationship that exists between scientific claims and experimental data. We suggest further that in order for students to develop robust set reasoning, there is a need to include in laboratory teaching the idea that scientific laws and theories are human constructs which need to be verified by experiments and are thus subject to revision.

It has been previously suggested (Allie et al., 2003) that one of the key stumbling blocks in understanding the nature of measurement is the statistical formalism of data analysis used in most introductory laboratory courses that relies on analysing data in terms of frequencies (and is hence often termed "frequentist"). In contrast, the probabilistic interpretation of measurement results in a framework in which the interpretation of uncertainty is clearer and more tangible, and provides a coherent way for evaluating uncertainties of single and multiple measurements (Allie et al., 2003). In the probabilistic framework the data are regarded as the manifestations of the phenomenon, and are treated as constants, while it is the inference that is made about the measurand which has a degree of uncertainty associated with it. The measurement result is interpreted as a statement of the available *knowledge* or information about the measurand, an approach which we believe provides persuasive pedagogic opportunities. We have designed and implemented a course (Buffler, Allie, Lubben & Campbell, 2007) based on the probabilistic framework of metrology which provides opportunities for students to explore the nature of uncertainty in measurement through activities which challenge notions of measurement yielding an exact (point-like) result, which has been shown to have distinct advantages for teaching and learning (Pillay, Buffler, Allie & Lubben, forthcoming).

In conclusion, we suggest that at the introductory tertiary level, an appropriate understanding of scientific *measurement* depends critically upon an appropriate understanding of the nature of *uncertainty* in measurement. We argue further that laboratory curricula should highlight the interplay between theory and experimental data, and that the reporting of scientific measurement, as a form of scientific evidence, requires that quality of the knowledge be communicated (in the form of a numerical uncertainty) in a consistent way. The conceptual underpinnings that allow numerical estimates of uncertainties to be generated appropriately should therefore also form part of the introductory physics laboratory. Laboratory activities which promote an appropriate view of the nature of scientific measurement will therefore aid the development of appropriate views of the nature of scientific evidence, which supports science as a discipline.

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Table 1. Descriptors defining the four NOS profiles.

Aspect of the NOS	*Profile 1 Modellers*	*Profile 2 Experimenters*	*Profile 3 Examiners*	*Profile 4 Discoverers*
The nature of scientific knowledge	Scientific knowledge explains or describes the behaviour of nature and is based on experimental evidence.	Scientific knowledge explains or describes the behaviour of nature and is based on experimental evidence.	Scientific knowledge explains or describes the behaviour of nature and is based on experimental evidence.	Scientific knowledge explains or describes the behaviour of nature.
The origin of laws or theories	Scientific theories are constructed from observations for better understanding of the complex behaviour of nature.	Scientific theories are constructed from observations for better understanding of the complex behaviour of nature.	Nature has its own laws which are discovered through observation.	Nature has its own laws which are discovered through observation.
The purpose of scientific experiments in relation to theories	Theories are tested, validated and confirmed through experimentation.	Theories are tested, validated and confirmed through experimentation.	Theories are tested, validated and confirmed through experimentation.	Theories are tested, validated and confirmed through experimentation.
The role of creativity in scientific experimentation	Scientists may use their creativity when undertaking experiments to be successful by making new discoveries and improvements.	Scientists strictly use the scientific method when undertaking experiments as they must be successful and have accurate results.	Scientists may use their creativity when undertaking experiments to be successful by making new discoveries and improvements.	Scientists strictly use the scientific method when undertaking experiments as they must be successful and have accurate results.
The precedence of theoretical and experimental results	If experimental results and theories disagree, then both need to be checked.	If experimental results and theories disagree, then the experimental results are likely to be correct.	If experimental results and theories disagree, then the experimental results are likely to be correct.	If experimental results and theories disagree, then both need to be checked.

Table 2. Reponses to the NOS probes of a student (274) classified as a 'modeller'.

Aspect of the NOS	*Quote*
The nature of scientific knowledge	'Scientific knowledge is the collective information humans have gathered about the universe and ourselves. It is made up of theories which seem to explain some part of the real world, and although they cannot be proved to be true, knowledge is gained by measurements and rigorous testing of the subjects involved. Scientific knowledge is objective, and based as far as possible on facts'.
The origin of laws or theories	'Most scientific theories cannot be proved, but are only considered true because they appear to be consistent with all observations of nature so far. Scientists make observations, which can be inaccurate, and then create an explanation for the observations. The theories are man-made constructs, not necessarily fixed natural laws'.
The purpose of experiments in relation to theories	'Scientific knowledge can be gained from experiments or from existing theories. Scientific experiments give measurements and observations which can enable scientists to create a new theory or predict other results and better understand some concept. Existing theories can be modified to include topics other than the one they were designed to explain, so they can create a better understanding and knowledge about something previously unknown'.
	'The purpose of an experiment is to test a scientific hypothesis which predicts the behaviour or outcome of objects or concepts. It is designed to either give a contradictory outcome, disproving the hypothesis, or to produce consistent outcomes, increasing the credibility of the hypothesis. Its purpose is to create a controlled environment, eliminating unnecessary variables to get accurate measurements and cause-and-effect relationships'.
The role of creativity in scientific experimentation	'Nothing new can be discovered without some creativity in science, and sometimes new methods are necessary to gain new knowledge. However, for the results of an experiment to be accepted, they should be consistent both when using the creative method and when using the scientific method'.
The precedence of theoretical and experimental results	'The scientists should re-examine both their theory and their experimental method and look for any errors in measurement or discrepancies between them. If the theory is definitely predicting the same quantity as the experiment is actually measuring, and the measurement is agreed to have been accurately measured then the scientists should search for other factors which affect it which could be included in the theory, or completely revise it'.

Table 3. Reponses to the NOS probes of a student (229) classified as an 'experimenter'.

Aspect of the NOS	*Quote*
The nature of scientific knowledge	'Knowledge which has been tested by the scientific method; knowledge which empirical evidence supports entirely (in the case of empirical sciences); or knowledge which has been proved logically (in the case of the mathematical sciences). Knowledge which has been subjected to the process of peer review and which is accepted as truth by a large majority of the scientific community'.
The origin of laws or theories	'Scientists usually start the process of discovery with experimental / empirical observation. The data from observation is then analysed to determine if a relationship exists. If there is a relationship, it is tested against further evidence. Laws which were thought to be "exact" laws of nature are sometimes proved to be wrong and superseded by more accurate laws; e.g. the super session of Newtonian (classical) mechanics by relativistic mechanics'.
The purpose of experiments in relation to theories	'New scientific knowledge can result either from experiments or from knowledge. In some cases, new theories arise from the experimental evidence; in other cases, theories predict results which are then tested by experiments'. 'The main purpose is to confirm (or deny) the truth of a proposed theory. If the experimental results agree with the theory, that supports the suggestion that the theory is true. If the evidence disagrees then the theory must be false'.
The role of creativity in scientific experimentation	'To be creative while performing an experiment and deviate from the agreed-upon method, would jeopardize the accuracy and correctness of the results. It would also make published results less likely to be accepted by the scientific community'.
The precedence of theoretical and experimental results	'First they need to determine whether any factors not accounted for in the theory have influenced their results. If all factors not accounted for by the theory have been eliminated, then they need to revise the theory to explain the anomaly'.

Table 4. Reponses to the NOS probes of a student (385) classified as an 'examiner'.

Aspect of the NOS	*Quote*
The nature of scientific knowledge	'It's knowledge of how and why things work. Something is a science when we get to know how it works. When we have more detailed understanding of things and when we know something in depth. In scientific knowledge we see how things relate to each other'.
The origin of laws or theories	'I once heard some one say that most inventions happen by accident which I think is true. Just like theories and scientist discover it. Everything in nature works in a certain way and has reason why it functions in that way, we can thus say it follows laws'.
The purpose of experiments in relation to theories	'The more scientific experiments we do, the more scientific knowledge we obtain. Experiments allow you to understand things from different points of view and could allow you to discover something new'.
	'You have an aim and you predict what should happen before experimenting. The point of experimenting is to see if your predictions came true. You could also experiment to see how things work under different circumstances. Thus giving more knowledge and understanding of the thing you are experimenting'.
The role of creativity in scientific experimentation	'In my opinion both method should be tested, this allows for as much information as possible to be obtained. Using creativity can also make science interesting'.
The precedence of theoretical and experimental results	'They should do the experiment a few more times and try and change some of the conditions/surrounds. And if the new result still does not agree with their theory, they should use the new information to obtain a new theory'.

Table 5. Reponses to the NOS probes of a student (285) classified as a 'discoverer'.

Aspect of the NOS	*Quote*
The nature of scientific knowledge	'Scientific knowledge is knowledge that contains scientific understanding. Any knowledge that is rational and logic and is about the study of the properties of the universe, is considered as scientific knowledge'.
The origin of laws or theories	'Basically laws governing nature has been there or around all the time. It is the scientists job to discover it and make use of it if needed. For example gravity was there all along. It was waiting quietly for Newton to discover and understand it'.
The purpose of experiments in relation to theories	'New scientific knowledge are not entirely based on results from scientific experiments. It is based on existing scientific theories because theories are not 100% true. So, scientific knowledge can change depending on the truth or total understanding of the scientific theory'.
	'There are several reasons why we use experiments. It could be used to prove a certain theory. It could be used to challenge another theory or knowledge of science. And another purpose of scientific experiments is that it is used to clarify or show that something is right or wrong, depending on the something so that we may gain an understanding of it'.
The role of creativity in scientific experimentation	'Scientists always use the "Scientific Method" especially during experiments. By being creative they could fail to understand the nature of the law or discovery. Only if the "Scientific Method" fails can they perhaps seek different ways'.
The precedence of theoretical and experimental results	'They should revise their theory and hopefully figure-out a solution. If the theory seems correct then they should use different measuring equipment'.

Table 6. Descriptors defining the point and set paradigms.

Point paradigm	*Set paradigm*
The measurement process allows you to determine the true value of the measurand.	The measurement process provides incomplete information about the measurand.
"Errors" associated with the measurement process may be reduced to zero.	All measurements are subject to uncertainties that cannot be reduced to zero.
A single reading is potentially the true value of the measurand.	All available data are used to construct distributions from which the best approximation of the measurand and an interval of uncertainty are derived.

Table 7. Relationship between the students' views on the NOS and the nature of scientific measurement.

	Profile 1 Modellers	*Profile 2 Experimenters*	*Profile 3 Examiners*	*Profile 4 Discoverers*	*Not classified*	*Total*
Point paradigm	51 (65%)	21 (72%)	30 (88%)	10 (77%)	19 (76%)	131 (73%)
Set paradigm	19 (25%)	6 (21%)	3 (9%)	3 (23%)	4 (16%)	35 (20%)
Not classified	8 (10%)	2 (7%)	1 (3%)	0 (0%)	2 (8%)	13 (7%)
Total	78 (100%)	29 (100%)	34 (100%)	13 (100%)	25 (100%)	179 (100%)

Table 8. Ratio of students associated with point over set paradigm for each profile.

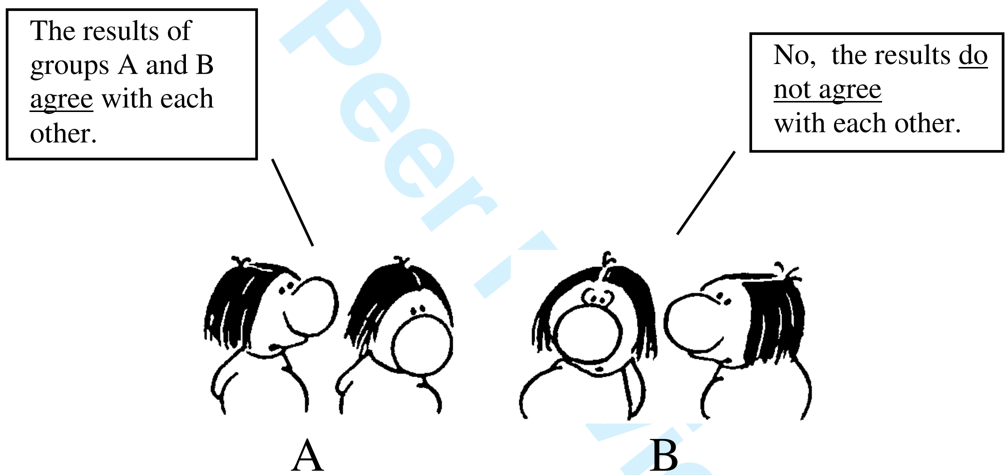
Profile	*Ratio*
Profile 1 (Modellers)	51/19 = 2.7
Profile 2 (Experimenters)	21/6 = 3.5
Profile 3 (Examiners)	30/3 = 10.0
Profile 4 (Discoverers)	10/3 = 3.3
Overall	**131/35 = 3.7**

Table 9: Relationship between students' views of the origin of scientific laws and theories, and their views on measurement.

		Views about measurement			*Total*
		Point paradigm	*Set paradigm*	*Not classified*	
Views about the origin of laws and theories	Nature has its own laws which are discovered.	64 (49%)	7 (20%)	3 (23%)	74 (41%)
	Scientists construct theories from observations.	57 (43%)	26 (74%)	8 (62%)	91 (51%)
	Not classified.	10 (8%)	2 (6%)	2 (15%)	14 (8%)
	Total	131 (100%)	35 (100%)	13 (100%)	179 (100%)

The scientists now decide to compare their results with the results obtained by another group of scientists for the same experiment. The data are shown below.

Measurement	Group A Magnetic field (mT)	Group B Magnetic field (mT)
1	0.137	0.128
2	0.128	0.140
3	0.138	0.134
4	0.128	0.127
5	0.134	0.126
Average:	**0.133**	**0.131**



With which group do you most closely agree? (Circle ONE): A B

Explain your choice. Do not use the word "results" in your explanation.

Figure 1. One of the VASM probes in full, in this case dealing with the comparison between sets of measurements.